Mathematical Modeling and Computer Simulation of a Combined Cycle Power Plant

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Abstract. This paper presents the simulation procedure developed to predict the performance of a combined cycle power plant from given performance characteristics of its main components. Effects of gas turbine and steam turbine cycle parameters on combined cycle power plant (CCPP) output in terms of efficiency, work output and power output, particularly analyzing the influence of ambient conditions on the plant performance. The results of the mathematical model, implemented in ''Matlab'' software, have been compared with the simulation results presented in literature. Result shows that as the compression ratio increase the increase in efficiency becomes less. Increase in work output is observed upto a pressure ratio of 18 after this it starts decreasing. Increase in TIT increases cycle work output and efficiency. Turbine outlet temperature decreases with increase in compression ratio. Combined cycle efficiency and output first increases with rise in drum pressure and then decreases. Increasing superheater temperature is found to increase the specific work output and efficiency of steam and combined cycle. Increasing superheater temperature is found to increase the specific work output and efficiency of steam and combined cycle. Lowering the pinch point and approach point also results in an improvement in the combined cycle performance, Specific heats are considered to be changing with temperature. The present work will make the base for exergy analysis of combined cycle for varying parameters.

Keywords: Combined cycle power plant, TIT, inlet air temperature, compression ratio.

1 Introduction

A combined cycle power plant derives its name from the fact that a gas turbine engine, which operates on the Brayton cycle, is combined with a heat recovery steam generator (HRSG) and steam turbine system, which operates on the Rankine cycle. Combined-cycle efficiency improvements have been led by advances in gas turbine performance resulting primarily from higher firing temperatures (TIT).

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Kotowicz and Bartela [1] studied the influence of fuel price variations on the steam part of a combined cycle power plant, by means of a genetic algorithm based optimization programme. Poma et al. [2] improved the initial design of a waste-to-energy plant integrated with a combined cycle through a thermoeconomic procedure, and accomplished a reduction in the unit cost of electricity and an increment on the power production. Mussati et al. [3] presented a hybrid methodology which is able to provide lower and upper bounds on the economic optimal solution of combined heat and power plants and desalination systems, by using relationships between the thermodynamic and economic optima. Franco and Casarosa [4] showed how the thermal efficiency can rise over the actual limit of 60% for combined plants designed at its thermoeconomic optima, based on the minimization of the total cost of the plant per unit power, obtained referring to a common economic basis the cost of the exergy losses and the costs of the components. Valdés et al. [5] presented a thermoeconomic optimization model regarding the HRSG of a combined cycle plant, and as result showed that it is possible to find an optimum for every selected design parameter, although such optimum depends on the selected optimization strategy. The first part of this paper presents a discussion about the CCPP modeling approach. The second part includes CCPP computer simulation program and its philosophy. In the last performance of CCPP is analyzed for different operating parameters.

2 Mathematical Modeling and Computer Simulation Strategy

Combined cycle power plant (CCPP) considered for the present analysis is shown in figure.1. The air at the ambient temperature is compressed by the air compressor and directed to the combustion chamber. The compressed air mixes with the natural gas from the fuel supply system to produce hot combustion gas in the combustor. The hot combustion gas is delivered to the gas turbine where the power is generated. The exhaust gas passes through a heat recovery steam generator where water is converted to high pressure steam. The high pressure steam from the boiler drives the steam turbine. The spent steam from the turbine flows into the condenser. The steam is separated in the boiler drum and supplied to the super heater section and the boiler condenser section. The super heated steam produced in the super heater then enters into the turbine through the turbine stop valve. After expansion in the turbine the exhaust steam is condensed in the condenser. To determine the performance of the CCPP, each component must be modelled. CCPP with waste heat recovery and utilization system is modelled in consideration of mass, and energy balances for every component. The task of computer simulation involves predicting the operating conditions of the system (pressures, temperatures, energy and fluid flow rates) at which various mass and energy balances, all equations of state of working substances and the performance characteristics of the individual components are satisfied. A HRSG is a series of heat exchangers – economizers to heat water close to saturation, evaporators to produce

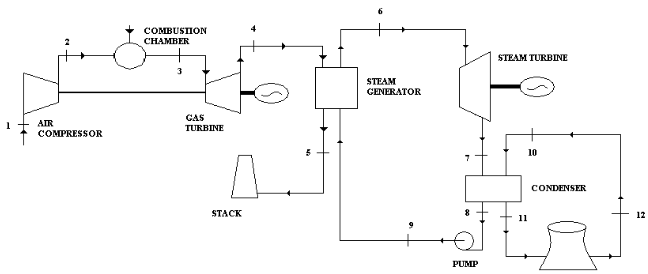

Fig. 1. Schematic flow diagram of a simple combined cycle power plant

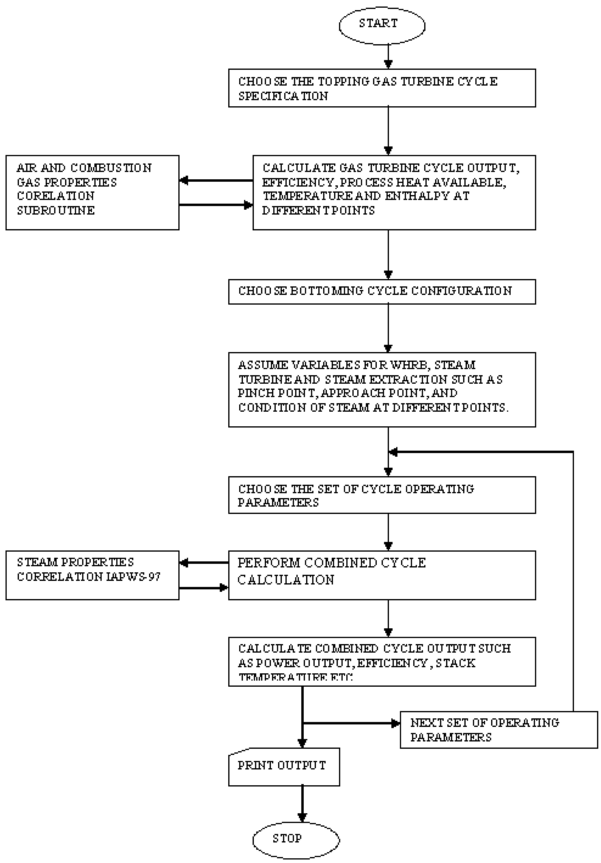

Fig. 2. Information flow diagram for design philosophy of a simple CCPP

saturated steam and superheaters to produce superheated steam. A relatively simple HRSG design will operate at a single water/steam pressure through the Rankine cycle circuit, but in an effort to extract the maximum amount of energy from the gas turbine exhaust gas there may be one or two higher pressure circuits added to the system. Each added pressure level increases power output from the steam turbine, but the complexity and cost of the HRSG system and the steam turbine are also increased. HRSG is an interface between the gas cycle and the steam cycle in combined cycles. The classical approach to HRSG optimization is the "pinch-point" method, i.e. imposing the minimum temperature difference between the two agents [7]. The factors which effect the cost and effectiveness of any WHRB are the pinch point, approach point, allowable back pressure, stack temperature, steam pressure and steam temperature. The minimum temperature difference for heat transfer, which is known as pinch point plays an important role in identifying the optimum heat recovery and size of heat exchangers. Approach point is the difference between the saturation temperature and the temperature of water leaving the economizer. Lowering the approach point will increase the probability of steaming in economizer which may cause hammering and blanketing. Detailed mathematical modelling may be had from somewhere else [6].A computer simulation model in MATLAB has been developed to simulate the performance of combined cycle power plants.

2.1 Combined Cycle Power Plant Computer Simulation

A computer program for simulating a combined cycle power plant would basically satisfy matching conditions analytically between the various components to produce the matching between different components for optimum performance. Representing this either in the form of lookup tables or an equation is known as modeling and solving that equation with the help of a computer is computer simulation such that all energy and mass balances, all equations of state of working substances, and the performance characteristics of all components are satisfied. Testing of the combined cycle power plant is expensive and time consuming. Therefore, simulation can be an economic and fast tool for predicting its performance. The simulation of the combined cycle power plant can be one of the following
applications:

1. Simulation at the design stage for gas turbine engine to meet the design specifications of the steam power plant for retrofitting.
2. Simulation at the design stage where no real combined cycle power plant exists to meet the design specifications.
3. Simulation at the application stage where the generation of design data for additional or auxiliary equipment, such as lubricating oil requirements, blow off valve requirements, and limitations for transformers, etc., are needed.
4. Simulation for performance extrapolation of existing plant at part load or for efficiency improvement.

In the figure.2 a generalized design philosophy of a simple CCPP is shown in the form of a flow chart.

2.2 Computer Simulation Program

The computer simulation program uses the components models based on either mathematical equations or performance characteristics to achieve matching between the various components in the combined cycle power plant. The programme can be used to calculate the effect of different CCPP performance parameters. The principal advantages of CCPP simulation program would be as follows

1. The computer simulation program can help in investigating the effects of the components performance characteristics on the performance of the complete cycle. This investigation can be carried out at the design stage without bearing the cost of manufacturing and testing an expensive prototype.
2. The conceptual designs of the GT, ST, HRSG and compressor can be studied and the choice of particular concept can be made to suit the specified operational requirements.
3. The matching of the components can be explored for the design, off-design, and transient conditions.
4. The simulation program can serve as a valuable tool for investigating the performance of the plant at off design conditions. This investigation can help in designing an efficient control system for the combined cycle power plant.

In 1997, the International Association for the Properties of Water and Steam (IAPWS) adopted a new formulation for the thermodynamic properties of water and steam for industrial use. This new formulation, called IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam (IAPWS-IF97), replaces the previous industrial formulation, IFC-67, that had formed the basis for power-plant calculations and other applications in energy engineering since the late 1960's. IAPWS-IF97 improves significantly both the accuracy and the speed of the calculation of the thermodynamic properties compared with IFC-67. Results obtained from the program are discussed in the following section.

3 Results and Discussion

Gas turbines used in the combined cycle power plants are having pressure ratios below 15. For the present analysis cycle compression ratio is varied from 8 to 20. In actual practice a gas turbine gives maximum efficiency at different pressure ratio than that for maximum work output. So the compression ratio is kept in between these two ratios. As the compression ratio is increased the maximum temperature at the outlet of compressor is increased. The fuel requirement is decreased because turbine inlet temperature is fixed. Gas turbine inlet temperature is fixed by the thermal stress bearing limit of the turbine blade material. If the compression ratio of the gas turbine has to be increased in that case size of the blade will be larger and inertia force will increase. To bear this larger inertia force, a strong blade base is required. In a combined cycle power plant waste heat

coming out from the gas turbine may be utilized in heat recovery steam generator to generate steam which will be passed from the steam turbine to generate CC plant could lose as much as 10 to 15 percent of its rated ISO output. Ambient air temperature never remains constant. Now from the analysis it is being found that as the IAT will increase fuel requirement will decrease. This is due to the fact that TIT is fixed for this case and if the IAT increases then combustion chamber inlet temperature will also increase. But combustion chamber outlet temperature is fixed. So the fuel requirement decreases. For the design conditions if the TIT is fixed then, as the gas turbine inlet temperature will keep on increasing then the fuel requirement will decrease. But due to the increase in the ambient temperature the mass flow rate of the air to the compressor also decrease which leads to the lesser work output and lesser efficiency. Inlet air cooling may bring the ambient air to the designed condition. Effect of increase in compression ratio is positive on the combined cycle efficiency but that of IAT is negative. With the increase in IAT combined cycle efficiency comes down. As the inlet air temperature increases, fuel consumption is not decreased much but decrease in work output is high. Due to this reason efficiency of combined cycle decreases with increase in ambient air temperature. Highest TIT is decided by the metallurgical stress bearing capacity of turbine blade material. With the higher TIT larger is the fuel consumption and work obtained in the cycle and combined cycle efficiency also increases. For designing the gas turbine the compression ratio is kept between the maximum work and maximum efficiency. Increasing the TIT increases combined cycle efficiency. Benefit of increasing a lower temperature is more and it decreases with TIT. It is so due to increase in the consumption of fuel to attain higher TIT. After a turbine inlet temperature of 1700 K not much increase in efficiency is observed. In combined cycle work is obtained from the gas turbine and as well as from the steam turbine. With increase in turbine inlet temperature (TIT) work output of gas turbine is not changed but gases come out from gas turbine at higher temperature. So more heat is available in HRSG for the water to be converted into steam. Due to this reason work output of steam cycle increases and hence the net output of combined cycle. With increase in TIT fuel consumption increases and as well as work output also increases. In this case effect of increase in work output is more pronounced than that of increase in fuel consumption. So net efficiency of combined cycle increases with increase in TIT.

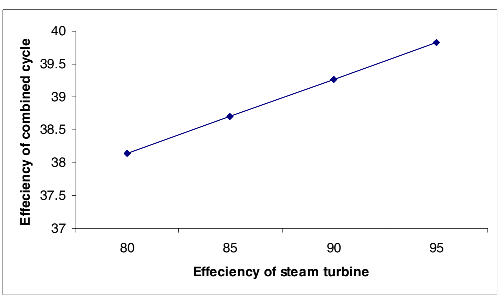

Fig. 3. Change in combined cycle efficiency with change in steam turbine efficiency.

Efficiency of steam turbine cycle is directly affected by steam turbine efficiency. As the steam turbine efficiency increases, efficiency of combined cycle also increases. For the present analysis steam turbine efficiency is varied from 80% to 95% and it is found that combined cycle efficiency increases from 38.14% to 39.83%. Effect of steam turbine parameter is less pronounced than that of gas turbine parameters.

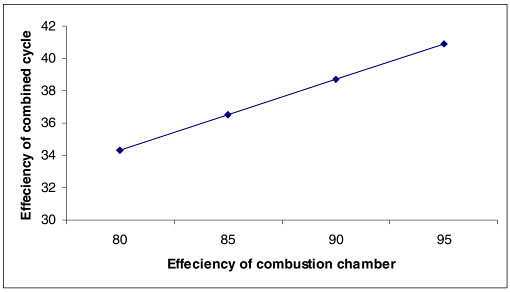

Fig. 4. Change in combined cycle efficiency with change in combustion chamber efficiency.

Effect of combustion chamber efficiency is linear on the combined cycle efficiency. Combustion chamber is having many types of losses. For the present analysis combustion chamber efficiency is varied from 80% to 95%. As the combustion chamber efficiency will be increasing more enthalpy will be going to gas turbine and more heat will be transferred to HRSG. Due to which combined cycle efficiency will be increasing. With increase in combustion chamber efficiency by 15% there is an increase of combined cycle efficiency by 6.6%. It is shown in figure.4.

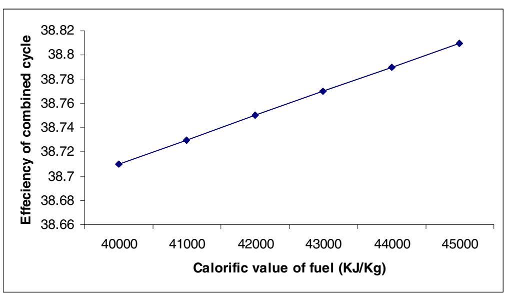

Fig. 5. Change in combined cycle efficiency with change in calorific value of fuel.

In the present analysis lower heating value of the fuel is taken into consideration. It is being found that with increase in calorific value of fuel cycle efficiency is increased. Fuel supplied to the plant is natural gas and its composition varies from place to place and hence its calorific value. In the present analysis it is being found that with change in calorific value from 40000 KJ/Kg to 45000 KJ/Kg

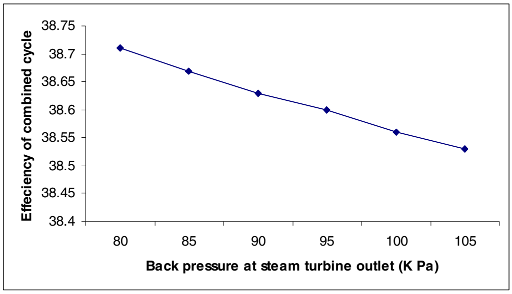

Fig. 6. Change in combined cycle efficiency with change in back pressure at steam turbine outlet.

combined cycle efficiency is varied by only 0.10% (figure.5.). So the calorific value is having very less effect on the combined cycle performance. Back pressure is the pressure at which steam comes out of the steam turbine. For the higher efficiency it is kept as low as possible. In the present work value of back pressure is varied from .080 atmosphere to .105 atmosphere and it is being found that combined cycle efficiency is decreased by 0.18% (figure.6). From the figure.7 it may be seen that as the drum pressure is increased, combined cycle efficiency comes down. With the change in drum pressure from 12 bar to 17 bar cycle efficiency is decreased by 0.85%. Pinch point (PP) temperature is generally kept 8°C and an approach point of 2°C is taken. So we can take a pinch point of 10°C. In figure.8 it is shown that with increase in pinch point from 5°C to 25°C, combined cycle efficiency is decreased by 0.18%. As the PP is increased, decrease in efficiency is lesser but after that it is increased. Combustion turbine performance has the primary impact on combined cycle plant efficiency. The next most important piece of equipment that impacts efficiency is the heat recovery steam generator. The HRSG parameters to optimize include steam pressures, temperatures, flows, pinch points, approach temperatures, and HRSG exit gas temperatures. The energy analysis is not sufficient for accurate prediction of combined cycle power plant

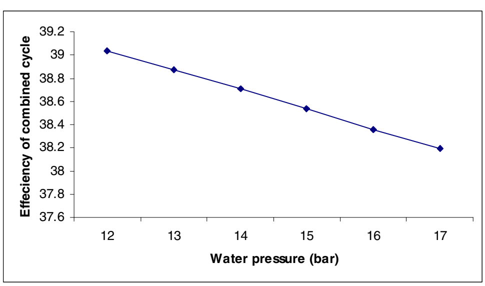

Fig. 7. Change in combined cycle efficiency with change in pressure at steam turbine inlet.

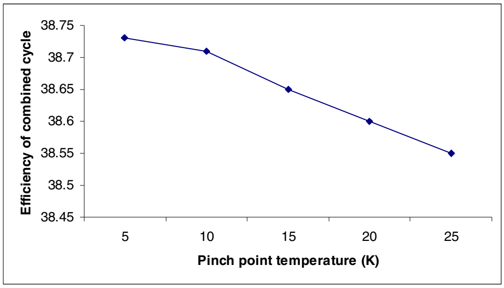

Fig. 8. Change in CCPP efficiency with change in pinch point temperature.

performance. Energy analysis gives only idea about the efficiency and work obtained from the cycle. It does not tell us about the major sites of energy losses. For the complete analysis exergy analysis is also required. The present work makes a base for the exergy analysis.

4 Conclusion

1. For a single pressure WHRB as the drum pressure increases, the main steam flow rate falls down. This is due to fact that with the increase of drum pressure steam temperature approaches nearer to the exhaust gas temperature, due to which heat recovery is reduced.
2. As the drum pressure increases the saturation temperature increases. Due to which as the drum pressure increases the enthalpy difference across the turbine increases.
3. Combined cycle efficiency and output first increases with rise in drum pressure and then decreases. This is obviously the result of combined effect of change in mass flow rate and enthalpy drop across the turbine.
4. With the increase in drum pressure the steam turbine cycle efficiency increases continuously, as the enthalpy rise is very high. Increasing superheater temperature is found to increase the specific work output and efficiency of steam and combined cycle even though simultaneously, the energy recovered in heat exchanger is reduced, which reduces steam mass flow rate.
5. Increasing the condenser pressure decreases the steam turbine and combined cycle output. The condenser pressure is strongly dependent on the cooling water flow rate, its temperature, and the design of condenser.
6. Lowering the pinch point results in an increase in the total heat recovered in the boiler, which therefore requires more heat exchanger surface area with a consequent increase in cost and gas side pressure drop. It of course increases the output and efficiency of the combined cycle.
7. Lowering the approach point also results in an improvement in the combined cycle performance, due to increase in steam production. Lower approach point would increase the surface area required in the evaporator section, and also increases the probability of damage due to steaming and hammering in economizer.

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